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IDENTIFICATION OF PUTATIVE GEOGRAPHICALLY ISOLATED WETLANDS OF THE CONTERMINOUS UNITED STATES

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IDENTIFICATION OF PUTATIVE GEOGRAPHICALLY ISOLATED WETLANDS OF THE CONTERMINOUS UNITED STATES[1]

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ABSTRACT: Geographically isolated wetlands (GIWs) are wetlands completely surrounded by uplands. While common throughout the United States (U.S.), there have heretofore been no nationally available, spatially explicit estimates of GIW extent, complicating efforts to understand the myriad biogeochemical, hydrological, and habitat functions of GIWs and hampering conservation and management efforts at local, state, and national scales. We used a 10-m geospatial buffer as a proxy for hydrological or ecological connectivity of National Wetlands Inventory palustrine and lacustrine wetland systems to nationally mapped and available stream, river, and lake data. We identified over 8.3 million putative GIWs across the conterminous U.S., encompassing nearly 6.5 million hectares of wetland resources (average size 0.79 ± 4.81 ha, median size 0.19 ha). Putative GIWs thus represent approximately 16% of the freshwater wetlands of the conterminous U.S. The water regime for the majority of the putative GIWs was temporarily or seasonally flooded, suggesting a vulnerability to ditching or hydrologic abstraction, sedimentation, or alterations in precipitation patterns. Additional analytical applications of this readily available geospatially explicit mapping product (e.g., hydrological modeling, amphibian metapopulation, or landscape ecological analyses) will improve our understanding of the abundance and extent, effect, connectivity, and relative importance of GIWs to other aquatic systems of the conterminous U.S.

(KEY TERMS: connectivity; data management; geospatial analysis; palustrine wetlands; rivers/streams/lakes; watershed management.)

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INTRODUCTION

Geographically isolated wetlands (GIWs) are freshwater wetlands "…completely surrounded by upland at the local scale" (Tiner, 2003a, p. 495). GIWs typically lack permanent surface water connectivity to other aquatic systems. However, GIWs may be connected by intermittent surficial waters (e.g., Leibowitz and Vining, 2003; Rains *et al.*, 2006; Wilcox *et al.*, 2011; Lang *et al.*, 2012; Vanderhoof *et al.*, 2015), groundwater and/or hydraulic processes (e.g.,

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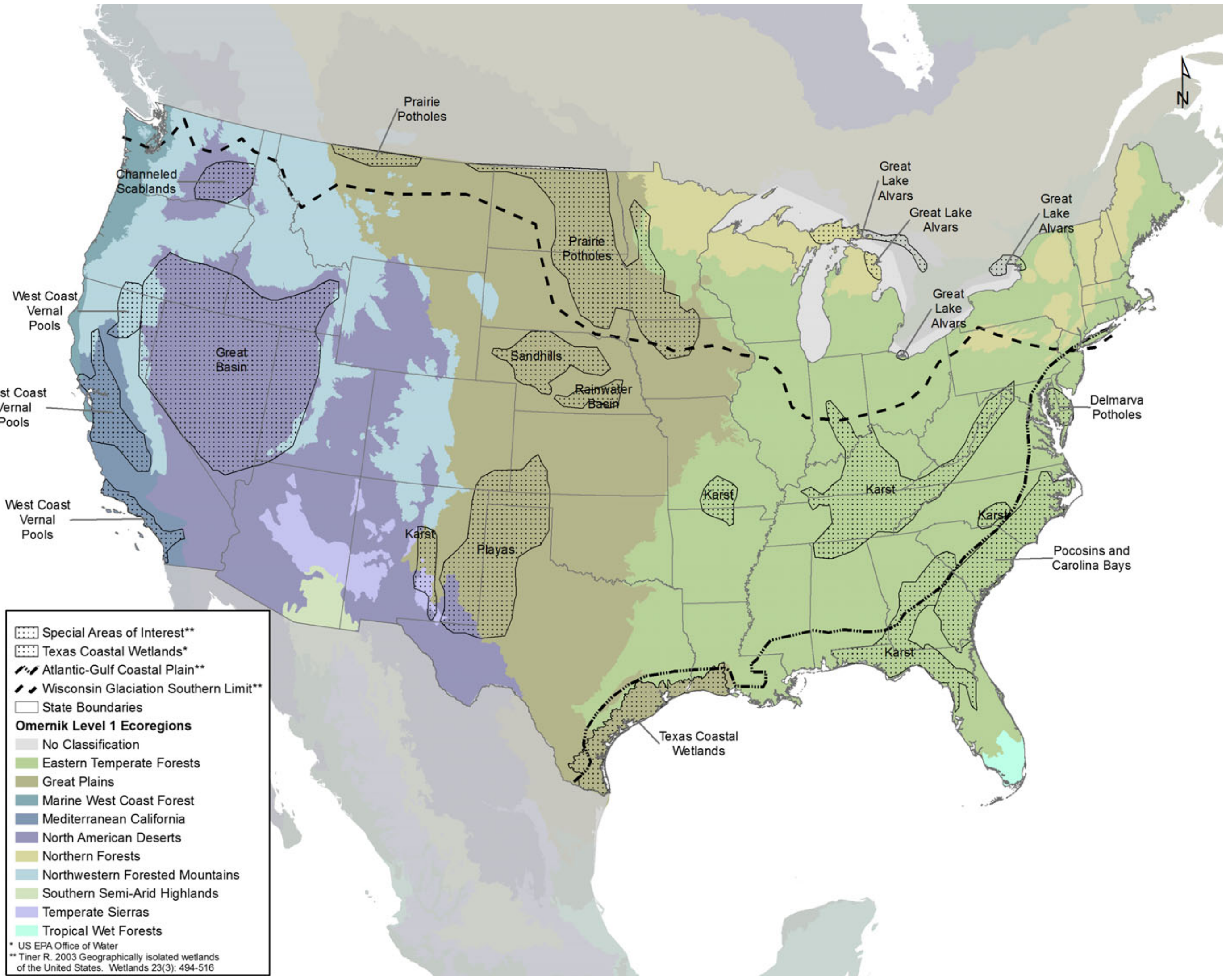

FIGURE 1. Special Areas of Interest (Tiner, 2003a) and Texas Coastal Wetlands with Known High Densities of Potential Geographically Isolated Wetlands Overlaying the Omernik (1987) Ecoregion Map. Texas Coastal Wetlands were derived from the Western Gulf Coastal Plain system (Omernik, 1987).

McLaughlin *et al.*, 2014), biological activities (e.g., Subalusky *et al.*, 2009), and biogeochemical processes (e.g., Creed *et al.*, 2003). These wetlands are common throughout the United States (U.S.) with certain areas of higher density (Figure 1, Tiner, 2003a); Comer *et al.* (2005) reported that 29% of 276 vegetatively based wetland ecological system types of the U.S. were geographically isolated. GIWs have been a controversial wetland landscape element (sensu Forman, 1995) since the 2001 *Solid Waste Agency of Northern Cook County* (SWANCC) *v. U.S. Army Corps of Engineers* (531 U.S. 159) U.S. Supreme Court decision created jurisdictional uncertainty of their regulation under the Clean Water Act (CWA) (Downing *et al.*, 2003; Adler, 2015). Recently, the U.S. Environmental Protection Agency (USEPA) and U.S. Army Corps of Engineers have promulgated a rule affecting GIWs and other waters, clarifying the scope of the CWA (Alexander, 2015). However, no maps of GIWs exist at the national scale, significantly hampering the ability of resource managers and the public alike to make informed policy decisions and creating the impetus for this study.

GIWs are typically small and shallow systems (Tiner *et al.*, 2002; Cohen *et al.*, 2016), readily ditched, drained, and/or filled for agricultural or development purposes. The U.S. has lost approximately half of the pre-European settlement wetlands (Dahl, 1990). Losses across areas of high GIW density (Tiner, 2003a) frequently exceed 90% (Dahl, 1990; McCauley and Jenkins, 2005). For instance, the Prairie Pothole Region (PPR) comprises almost 80 million ha straddling Canada and the U.S. and contains wetland resources critical to North American migratory waterfowl (NAWMP, 2012). Historically, GIWs across this region (typically prairie potholes) were estimated to cover almost 8 million ha (Mitsch and Gosselink, 2000). Dahl (2014) reported that approximately 88% of the wetlands in the PPR were in basins unconnected to streams, rivers, lakes, or other wetland complexes. More than half of the historical extent of PPR wetlands have been lost. In the Canadian portion of the PPR, Rubec (1994) estimated that upwards of 70% of the wetlands have been destroyed. In a southern portion of the PPR, Boland-Brien *et al.* (2014) reported that approximately 22% of Iowa was comprised of "poorly drained marsh-pothole landscape," but that 99% of the landscape was now artificially drained via tiles and ditching. Johnston (2013) reported wetland loses between 1980 and 2000 in the PPR in North and South Dakota of 5,200-6,200 ha/yr. Dahl (2014) reported annual losses in the PPR between 1997 and 2009 of 2,510 ha/yr. Wright and Wimberly (2013) found that croplands in the PPR, namely soy and corn, were encroaching upon the remaining (likely geographically isolated) wetlands. In South Dakota alone, nearly 100,000 ha of grasslands within a 100-m buffer surrounding wetlands were converted to soy or corn between 2006 and 2011 (Wright and Wimberly, 2013). Despite conservation efforts (e.g., Gleason *et al.*, 2011), GIWs in the PPR continue to be converted, ditched, or drained.

Additional studies focusing on different GIWs types (e.g., Tiner *et al.*, 2002) and North American regions have also reported substantial losses. For instance, Carolina Bays are depressional wetland systems that range from southern Georgia to southern New Jersey, with historical estimates of >500,000 bays in the region (Prouty, 1952). However, development, agricultural activities, and forestry have affected these systems (Sharitz and Gresham, 1998) such that in some cases (e.g., South Carolina; Bennett and Nelson, 1991), almost all the bays surveyed exhibited drainage ditches or scars. Playas are closed depressional wetlands of the southern Great Plains of the U.S. and northern Mexico — in one area of north Texas/eastern New Mexico, as many as 30,000 purported playas were identified, covering up to 720,000 ha (Luo *et al.*, 1999). Watershed erosion and subsequent sedimentation is decreasing playa wetland volume, concomitantly decreasing playa wetland hydroperiod. Holland (1978) estimated that agricultural activities and urban development destroyed approximately 90% of California's iconic vernal pools. McCauley *et al.* (2013) found that during a 20-year period, 26% of more than 3,000 geographically isolated cypress dome forested wetlands in central Florida were destroyed or degraded by urban development, and the impacts most affected the smallest and largest of the GIWs, leaving a disproportionate number of medium-sized systems.

North America's GIW resources cannot be properly managed if they cannot be identified and mapped. However, challenges to national-scale mapping of GIW resources are myriad. The data granularity and the working definition of "geographically isolated" (Tiner, 2003b; Leibowitz, 2015; Mushet *et al.*, 2015) frequently limit mapping estimates of current GIW extent, past losses, and modifications to the remaining wetland resources. Other factors confounding efforts to map GIWs including wetland size, the presence of obscuring vegetation, and data age (Ozesmi and Bauer, 2002; Adam *et al.*, 2010). For instance, national and state/provincial mapping and monitoring programs typically do not map many wetlands due to their small size. Minimum mapping unit values range from approximately 0.4 to 1.2 ha in the National Wetlands Inventory (NWI) (Tiner, 1997), one of the few nationally available geospatial wetland datasets, a size that excludes many GIWs. For example, Semlitsch and Bodie (1998) found that 46.4% of 371 Carolina Bay depressional wetland systems (a GIW type, Tiner *et al.*, 2002) in a 78,000-ha study area of South Carolina were ≤1.2 ha. Using aerial photography Burne (2001) and Lathrop *et al.* (2005) were able to identify potential vernal pools in areas of the Mid-Atlantic and northeastern U.S. with diameters from 9 to 14 m, demonstrating that abundant wetlands exist at scales smaller than most regional mapping efforts, and further demonstrating the challenges in quantifying the abundance and extent of GIWs.

Nevertheless, using geographic information systems (GIS) and remote sensing resources researchers have mapped the extent of putative GIWs in certain areas of the U.S. For instance, Lane *et al.* (2012) identified almost 1.2 million ha of GIWs across an eight-state region of the southeastern U.S. using GIS. Mapping of woodland vernal pools (Calhoun and deMaynadier, 2008) was conducted in Massachusetts (Burne, 2001) and New Jersey (Lathrop *et al.*, 2005), typically using leaf-off aerial photography. In Massachusetts, greater than 29,000 potential vernal pools have been identified (MHESP, 2014), while Lathrop *et al.* (2005) identified greater than 13,000 potential vernal pools in New Jersey. Bowen *et al.* (2010) mapped greater than 22,000 purported playa wetlands and other depressions in western Kansas using a combination of aerial photos, digital raster graphics (DRGs), and soil data. Martin *et al.* (2012) used DRGs, digital elevation models (DEMs), soils data, and NWI data to map GIWs in a large physiographic region of Georgia, finding that almost 20,000 more GIW hectares were identified when using integrated data sources than when using the NWI alone. Reif *et al.* (2009) used multiple GIS layers, including NWI and aerial photos, to map GIWs in a county in north-central Florida. Frohn *et al.* (2009, 2012) used satellite remotely sensed data (e.g., Landsat ETM+) to map GIWs in studied areas of Florida and Ohio, respectively; different methods were required in the different areas of the country due to vegetation, wetland size and mixed-pixels, and varying spectral signatures.

Likens *et al.* (2000) posited that no more than 20% of the wetland area of the conterminous U.S. are GIWs. Though smaller-scale studies noted above have identified wetlands purported to be GIWs, no assessments have been conducted at the national scale. The lack of knowledge on the national abundance, extent, and geospatial location of GIWs has left scientists and managers alike without the necessary information to fully understand the influence of GIWs on downstream systems and the consequences of GIW destruction or modifications. The goals of this study, the first of its kind, were to analyze and quantify the abundance, extent, and spatial distribution of putative GIWs across the conterminous U.S. It is important to note that this study used geospatial distance as a proxy for hydrological and ecological connectivity and isolation. Distance measures remain a simple, GIS-based approach to assess the potential abundance of an aquatic resource and we believe this study provides a starting point for further and more highly refined analyses. We provide timely baseline data on a wetland resource with biological (Subalusky *et al.*, 2009), biogeochemical (Marton *et al.*, 2015), and hydrological (Rains *et al.*, 2015) functions important to local and landscape processes (see Alexander, 2015; USEPA, 2015; Cohen *et al.*, 2016). As in this study we did not conduct field-based assessments of wetland connectivity and concomitant geospatial/surface-water-based isolation, we term the nonconnected wetlands "putative GIWs" (Lane *et al.*, 2012). We further maintained the convention of defining putative GIWs as those completely surrounded by uplands, while acknowledging that this construct, like most definitions in ecology, incompletely bounds a connectivity and/or isolation gradient (e.g., Tiner, 2003a; Leibowitz, 2015; Mushet *et al.*, 2015; USEPA, 2015).

METHODS

Geospatial Data

National Wetlands Inventory. We acquired the NWI on a state-by-state basis from the U.S. Fish and Wildlife, NWI server (U.S. FWS, various dates 2014-2015). We note that the definition of wetlands in the NWI differs from the regulatory definition of wetlands. That is, following Cowardin *et al.* (1979, p. 3), an NWI-defined wetland requires only one of the following three attributes: (1) predominantly hydrophytic vegetation, (2) predominantly hydric soils, or (3) saturated or ponded water during the growing season. For regulatory purposes under the CWA, a wetland requires all three (33 CFR 328.3(b)). We acknowledge the NWI has substantial limitations, including omissions and data age (Tiner, 1997; Lang *et al.*, 2012). However, the NWI was selected as the wetland geospatial data layer due to its national availability, resolution, and consistent terminology (e.g., it does not require a laborious cross-walking of terminology between studies).

For our analyses, we split the NWI data into two data layers by system definition (e.g., palustrine, riverine classes) for each state or portion thereof to facilitate the identification of putative GIWs (Table 1). We considered riverine and estuarine wetland systems *de facto* connected, or non-GIWs, and excluded them from analyses. On the other hand, palustrine and lacustrine polygons, by nature of their

TABLE 1. National Wetlands Inventory (NWI) System Definitions for Wetlands Included or Excluded from Analyses as Potentially Geographically Isolated Systems. We identified Marine, Estuarine, and Riverine systems as *de facto* nonisolated systems and excluded them from potential identification as geographically isolated wetlands.

System	NWI Definition (see Cowardin *et al.*, 1979, various pages)
Marine	"...open ocean overlying the continental shelf and its associated high-energy shoreline" (p. 4)
Estuarine	"...deepwater tidal habitats and adjacent wetlands that are usually semienclosed by land but have open, partly obstructed, or sporadic access to the open ocean, and in which ocean water is at least occasionally diluted by freshwater runoff from the land." (p. 4)
Riverine	"...all wetlands and deepwater habitats contained within a channel, with two exceptions: (1) wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens, and (2) habitats with water containing ocean-derived salts in excess of 0.5‰." (p. 9)
Lacustrine	"...wetlands and deepwater habitats with all of the following characteristics: (1) situated in a topographic depression or a dammed river channel; (2) lacking trees, shrubs, persistent emergents, emergent mosses or lichens with greater than 30% areal coverage; and (3) total area exceeds 8 ha..." (p. 11)
Palustrine	"...all nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses or lichens, and all such wetlands that occur in tidal areas where salinity due to ocean-derived salts is below 0.5‰." (p. 12)

typical location outside of or disconnected from lotic channels, were considered potential GIWs.

National Hydrography Dataset. We acquired the available 1:24,000 NHD from the USGS (2014) on a state-by-state basis. As with the NWI, the NHD is a seamless and nationally available geospatial data layer, the accuracy and spatial extent limitations of which were deemed acceptable for the national-scale goals of this study (e.g., Heine *et al.*, 2004; Lang *et al.*, 2012). A series of scripts were developed (Appendix 1) to extract and subsequently process the NHD components to identify putative GIWs (see below). The components extracted include Flowline, Waterbody, and Area. Streams and rivers (including perennial, intermittent, and ephemeral), canals and ditches and named artificial paths were included in the buffering process and identified from the Flowline component. Coastlines, as applicable, were also included. We selected lakes, ponds, and reservoirs from the Waterbody dataset, and selected polygons of streams and rivers — as differentiated from the Flowline data — from the Area dataset.

Geospatial Processing

National Wetlands Inventory. We converted NWI palustrine and lacustrine polygons to single-part polygons to verify that each polygon in the data layer was geographically distinct. Multi-part polygons occasionally occurred when a wetland polygon had more than one spatially unconnected area with the same unique identification code. We calculated new polygon area attributes for each single-part polygon. Due to the presence of "true arcs" in the NWI (curved segments in a polygon that have only vertices at the start, end, and midpoint with no intermediate vertices) which caused geoprocessing errors, the polygons were densified using the ArcGISTool Densify function, using a node distance of 0.5 m (version 10.x; ESRI, Redlands, California). Once we densified the data, we aggregated the palustrine and lacustrine polygons so that nested polygons were treated as a single complex. We maintained links to the original NWI attribute table for each polygon in our analyses to allow subsequent analyses of wetland type and other NWI attributes by wetland polygon.

The first states aggregated were in and around the PPR (North Dakota, South Dakota, Iowa, Nebraska, Montana, and Minnesota; see Figure 1). Following Lane *et al.* (2012), we aggregated the palustrine and lacustrine wetlands using the Aggregate Polygon routine available in ArcGIS (version 10.x; ESRI). Due to the lack of processing capacity, it was necessary to split each state into a series of tiles for analysis and aggregation, and then merge the tiles using scripting language (version 2.7; Python Software Foundation, Wilmington, Delaware). The cumbersome nature of this tile-by-tile processing prompted the development of a different approach using scripting along with the Polygon Neighbors tool (see Appendix 2), decreasing processing time and increasing analytical performance. Once we streamlined the process, we rapidly aggregated and characterized palustrine and lacustrine polygons from the NWI dataset on a state-by-state basis. We set the lower extent of viable polygons to 0.05 ha and removed polygons smaller than 0.05 ha from our analyses.

National Hydrography Dataset. We established geospatial connectivity of wetland to NHD features using a buffering process as described below. To avoid buffering small ponds and lakes present in both the NHD and NWI that could potentially be GIWs, we designed a procedure to define which polygons to buffer. All polygons in the NHD Waterbody dataset with the feature class of "Lakes" that were greater than eight ha and overlapped wetlands in the NWI were included in the buffered dataset (i.e., these systems were not considered wetland features but lake features and as such were included in the dataset of features that were buffered). Cowardin *et al.* (1979) described lacustrine systems using eight hectares as the minimum size. We buffered the remaining NHD Waterbody dataset polygons with data in the GNIS_Name field (other than "null") that were less than 8 ha and greater than 1.5 ha if they overlapped any wetlands in the NWI (i.e., they were considered lake features). Geographic names that populated the GNIS_Name field were frequently affixed to lakes and ponds, areas often typified by waters >2 m in depth (a Cowardin *et al.* [1979] lacustrine indicator). We chose a conservative minimum size class for named systems of 1.5 ha to decrease the likelihood that we would inadvertently be including lakes as potential GIWs. We excluded any polygon in the NHD Waterbody dataset designated as a water treatment facility from buffering. In addition, any polygons designated as aquaculture and not already removed from consideration were examined against aerial photographs (Bing Maps, Microsoft Corporation, Redmond, Washington; various dates 2013) to visually identify structures. We did not buffer any NHD polygon identified as involved in aquaculture.

Analysis and Assessment of Putative Geographically Isolated Wetlands. We implemented a buffer overlap analysis process to identify putative GIWs — those not adjoining other aquatic polygons — using the post-processed NWI polygons and buffered NHD data layers. The selected NHD Area, Waterbody, Flowline, and Coastline systems were buffered

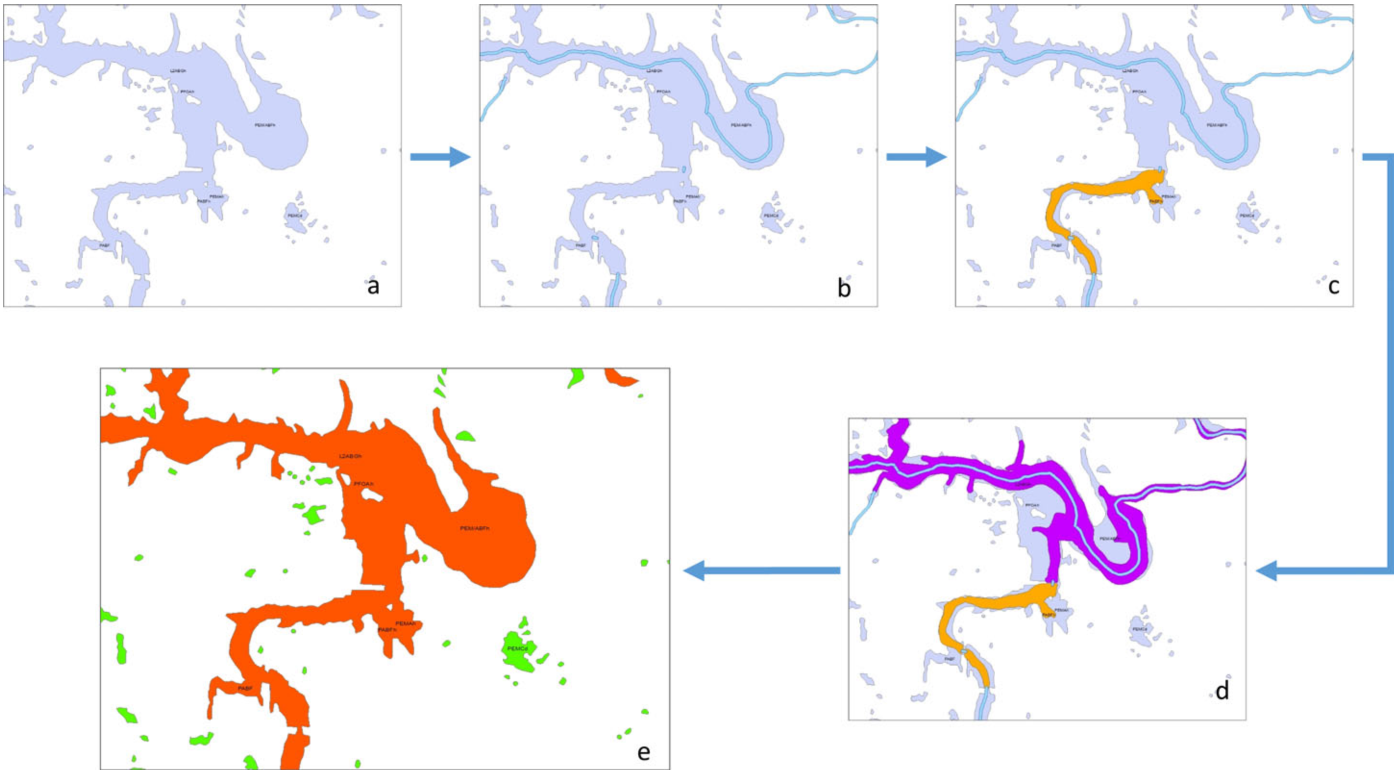

FIGURE 2. Example of the Buffering Process Used to Identify Putative Geographically Isolated Wetlands (GIWs): (a) Aggregated National Wetlands Inventory Polygons, (b) 10-m Buffering of National Hydrography Dataset (NHD) Flowline, (c) 10-m Buffering of NHD Area, (d) 10-m Buffering of NHD Waterbody, (e) Example Output (Green Polygons — putative GIWs; Red Polygons — not GIWs).

at 10 m. If a state abutted one of the North American Great Lakes, the boundary of the Great Lake (acquired from Natural Earth, NaturalEarthData.com, September 2013) was treated as coastline and buffered as described above. We considered an NWI polygon a putative GIW if it did not intersect the buffered NHD layers and was not connected to any riverine wetland (Figure 2). The 10-m buffer width approximates the lateral positioning error (~12 m) of NHD 1:24,000 data (USGS, 2014) and further approximates the buffer suggested by the Association of State Wetland Managers (2001) for quantifying connectivity. Though Tiner (2003b) analyzed select areas of the country at 20 and 40 m, we choose 10 m for the buffer as this builds from the body of literature using 10 m (e.g., Frohn *et al.*, 2009; Reif *et al.*, 2009; Frohn *et al.*, 2012; Lane *et al.*, 2012) and acknowledges horizontal limitations in the accuracy of the NHD data layer.

Areas Selected for Buffer Analysis. To address potential limitations of a 10-m buffer across the conterminous U.S., we explored the application of additional data buffering distances (30, 300 m) on the abundance of putative GIWs in five areas of the country with known high density of GIWs. We selected 30 and 300 m as additional exploratory distances that states or other geopolitical entities may deign to use to define geospatial-based connectivity. Four areas were identified by Tiner (2003a) as replete with GIWs: the PPR, West Coast Vernal Pools, Pocosins and Carolina Bays, and Delmarva Ponds (see Figure 1). We added an additional study area in southern Texas (Texas Coastal Wetlands), where recent studies have suggested connectivity between depressional wetlands and other aquatic systems (Wilcox *et al.*, 2011; Forbes *et al.*, 2012). We manually delimited the regional study areas following the data available in Tiner (2003a), with the exception that we used the Omernik (1987) Western Gulf Coastal Plain to define the boundary of the Texas Coastal Wetland study area. We reported each regional area independently from the state-by-state data (see below).

Quality Assurance and Control

We added three new attribute fields to the post-processed NWI polygons based on the outcome of the buffer analysis: AdjRiverine, AdjBuffer, and Isolated. If both AdjRiverine and AdjBuffer were null, we assigned the wetland polygon to the putative GIW class. We validated the final putative GIW dataset against potential geoprocessing errors through several steps. The first check matched the areal extent between the final GIW dataset and the original NWI attribute table, ensuring a true relationship between the original and aggregated data. We also confirmed that no NWI wetlands were omitted from our post-processed NWI data by comparing and confirming inclusion of all unique polygon-identifying labels. We compared the total area for each post-processed wetland polygon delimited as a putative GIW to the value in the original NWI attribute table. Additionally, we developed a process to ensure that putative GIW polygons that overlapped state boundaries were counted only once since statewide NWI data included wetlands that overlap state boundaries. The overlap extent varied between states with no obvious set distance. If a wetland polygon overlapped the boundary of two or more states, we assigned the wetland to the state with the highest proportion of wetland area. As a final output for each state, we exported the polygons delineated as putative GIWs and the associated attribute tables into a single geodatabase. We created an additional table summarizing the wetland class for each post-processed NWI polygon. An identifier unique to each post-processed NWI polygon linked both the tables and the polygons.

Example Applications of the Data

We demonstrated an application of the data potentially useful to amphibian ecology (Smith and Green, 2005; Mushet *et al.*, 2013) and calculated simple Euclidean distances between the edges of putative GIWs, and between putative GIWs and NHD features in the five areas selected for buffer analysis (see Figure 1). In addition, as the putative GIW database includes NWI water regime information for each identified wetland, we analyzed the abundance of water regimes by state. These hydrologic data range from permanently flooded to temporarily flooded. Water regime information may be useful to quantify biogeochemical cycling rates (Marton *et al.*, 2015) or assess emissions (e.g., Gleason *et al.*, 2009) at landscape scales. More intricate landscape-scale analyses of functions associated with GIWs are beyond the scope of this paper, but an example using an earlier version of these geospatial data is available (see Cohen *et al.*, 2016).

RESULTS

Potential Geographically Isolated Wetland Abundance

We identified nearly 8.4 million NWI polygons representing putative GIWs throughout the conterminous U.S. (Table 2). The total area of GIWs is approximately 6,594,813 ha, with the average size of 0.79 ± 4.81 ha (range 0.05-4,973.14 ha; median size 0.19 ha). Contemporary estimates of wetland extent within the conterminous U.S. suggests 44.5 million ha of wetlands exist, 95% of which are freshwater (Dahl, 2011). Using these areal values, we conclude that 15.6% of freshwater wetlands (14.8% of all wetlands) are putative GIWs.

As expected (see Tiner, 2003b), certain areas of the country had greater abundances of putative GIWs. The PPR, as well as the Atlantic and Gulf coastal plains had the greatest density of GIW areal abundance (Figure 3a). Due to the high number of small wetlands in the PPR, the count density (number of GIWs per km^2) was also remarkable in this ecoregion (Figure 3b), as also reported by Dahl (2014). Other areas notable for high areal or count densities include western Texas (playas; e.g., Luo *et al.*, 1999), Central California (vernal pools; e.g., Zedler, 1987; Rains *et al.*, 2006), Minnesota, northern Wisconsin, and central Michigan, as well as Massachusetts, southeastern New Hampshire, and southern and central Maine (woodland seasonal or vernal pools; e.g., Burne, 2001; Calhoun and deMaynadier, 2008).

Comparing 10-, 30-, and 300-m Buffers on National Hydrography Dataset Features

We calculated and compared the areal abundance of putative GIWs in five areas selected for buffer analysis (see Figure 1): PPR, Delmarva Peninsula, Pocosins/Carolina Bays, Texas Coastal Wetlands, and California Vernal Pools. Increasing the buffer width from 10 to 30 m resulted in areal decreases of GIWs ranging from −2.0 to −19.4%, with the least change in the PPR and the greatest decrease in California vernal pools (Table 3). However, when quantified as a proportion of the total freshwater habitat of a given area (i.e., the sum of palustrine, riverine, and lacustrine system areas), the net change was less notable, ranging from −0.7 to −2.7%, with the least change in Pocosins and Carolina Bays and the greatest in the Delmarva Peninsula. Approximately 50.8% of the freshwater habitat in the PPR was identified as putative GIWs using 10 m; this decreased slightly to 49.8% when a 30-m buffer was employed. Similarly, our analyses identified 30,685.92 ha of California vernal pools representing 5.8% of the freshwater habitat in the studied area as putative GIW using the 10-m buffer. This decreased to 4.7% of the freshwater habitat when we used a 30-m buffer. Increasing the analysis of connectivity by an order of magnitude (from 30 to 300 m) resulted in significant decreases in the abundance of putative GIWs. This was especially evident in areas with dense stream

TABLE 2. Areal Abundance of Potential Geographically Isolated Wetlands (GIWs) > 0.05 ha per km^2 by State, after Applying a 10-m Geospatial Buffer to National Hydrography Dataset Features and Overlapping the Output with the National Wetlands Inventory. Total freshwater wetland habitat by state was derived by combining the areal abundance of riverine, lacustrine, and palustrine wetland systems.

State	Count of GIWs	Area of GIWs (ha)	GIW % of Total Freshwater Wetland Habitat	State	Count of GIWs	Area of GIWs (ha)	GIW % of Total Freshwater Wetland Habitat	State	Count of GIWs	Area of GIWs (ha)	GIW % of Total Freshwater Wetland Habitat
AL	87,653	65,184	4.1	MA	73,608	45,464	18.1	OH	206,834	100,781	27.1
AR	151,560	90,425	7.9	MD	24,558	28,384	14.0	OK	285,878	80,425	10.8
AZ	12,274	11,734	3.5	ME	112,152	135,302	11.0	OR	58,719	47,206	5.2
CA	118,282	122,291	6.7	MI	324,427	459,713	15.3	PA	64,531	36,365	12.2
CO	114,421	69,646	9.6	MN	730,213	724,186	13.6	RI	6,454	5,344	15.8
CT	22,430	11,937	12.5	MO	439,735	99,190	13.4	SC	103,991	161,067	10.7
DC	27	42	12.2	MS	141,382	99,047	4.6	SD	652,277	485,216	46.3
DE	11,157	13,076	17.2	MT	183,725	102,241	12.2	TN	130,951	37,499	6.2
FL	318,973	584,714	12.7	NC	83,581	146,522	8.7	TX	631,225	444,599	17.0
GA	163,334	263,617	12.2	ND	1,149,022	700,861	48.5	UT	48,215	47,537	2.4
IA	126,636	52,118	12.6	NE	195,533	109,442	26.2	VA	64,906	47,338	8.7
ID	47,071	27,721	4.4	NH	29,357	19,697	10.5	VT	12,815	11,103	5.7
IL	145,167	78,716	10.7	NJ	21,969	28,396	9.6	WA	61,063	45,166	7.8
IN	172,181	108,953	22.2	NM	50,670	40,556	12.5	WI	183,293	338,349	10.0
KS	250,897	86,464	27.8	NV	10,023	32,094	3.2	WV	23,567	5,562	8.5
KY	179,850	46,466	13.0	NY	197,070	177,531	10.5	WY	113,553	59,705	10.1
LA	44,969	59,821	1.8					Totals	8,382,179	6,594,813	15.6

Note: AL, Alabama; AR, Arkansas; AZ, Arizona; CA, California; CO, Colorado; CT, Connecticut; DC, District of Columbia; DE, Delaware; FL, Florida; GA, Georgia; IA, Iowa; ID, Idaho; IL, Illinois; IN, Indiana; KS, Kansas; KY, Kentucky; LA, Louisiana; MA, Massachusetts; MD, Maryland; ME, Maine; MI, Michigan; MN, Minnesota; MO, Missouri; MS, Mississippi; MT, Montana; NC, North Carolina; ND, North Dakota; NE, Nebraska; NH, New Hampshire; NJ, New Jersey; NM, New Mexico; NV, Nevada; NY, New York; OH, Ohio; OK, Oklahoma; OR, Oregon; PA, Pennsylvania; RI, Rhode Island; SC, South Carolina; SD, South Dakota; TN, Tennessee; TX, Texas; UT, Utah; VA, Virginia; VT, Vermont; WA, Washington; WI, Wisconsin; WV, West Virginia; WY, Wyoming.

networks or in areas where the putative GIWs were located relatively close to lotic or lentic systems (e.g., in valley bottoms, ancient floodplain terraces, etc.; see Table 3). Delmarva ponds and California vernal pools decreased the most between the 30- and 300-m buffers, −76.0 and −69.6%, respectively. Potential GIWs in the PPR, with a relatively sparse stream network, decreased the least between 10 and 300 m, −21.6%.

Applications of the Data

Using the five areas selected for buffer analysis in this dataset as an example (see Figure 1), we calculated simple Euclidean distances between the edges of putative GIWs, and between GIWs and NHD features. Putative GIWs in areas of remarkable wetland density, such as the PPR, were spatially co-located proximal to one another (80.4 ± 106.2 m), while California vernal pools were on average 431.6 m (±580.2) from one another (Table 4). However, those PPR wetlands averaged >1 km from NHD features (1,112.8 ± 1,125.1 m), while California vernal pools averaged only 370.3 (±492.3 m) from an NHD feature.

We also analyzed the NWI water regime information for each putative GIW (Table 5). The most common water regime was seasonally flooded (27.5%), followed by temporarily flooded (22.9%), permanently flooded (14.9%), semipermanently flooded (14.0%), intermittently exposed (8.4%), saturated (6.4%), and seasonally flooded/saturated (3.2%). However, there was noticeable regionalization of the different water regimes that closely matched annual precipitation (Figure 4); areas of the U.S. with greater annual precipitation rates had greater abundances of permanent wetlands (though the New England region also had an abundance of seasonally flooded/saturated systems, likely reflecting the preponderance of vernal pools in the region).

DISCUSSION

The 2001 SWANCC ruling held that the presence of migratory birds was not by itself a sufficient basis for CWA jurisdiction for an "isolated" non-navigable intrastate water. Research to understand the functions, connectivity, and effect of GIWs to other systems has increased markedly since this time (Mushet *et al.*, 2015). A recent report by the USEPA (2015; see also Alexander, 2015), as well as several review

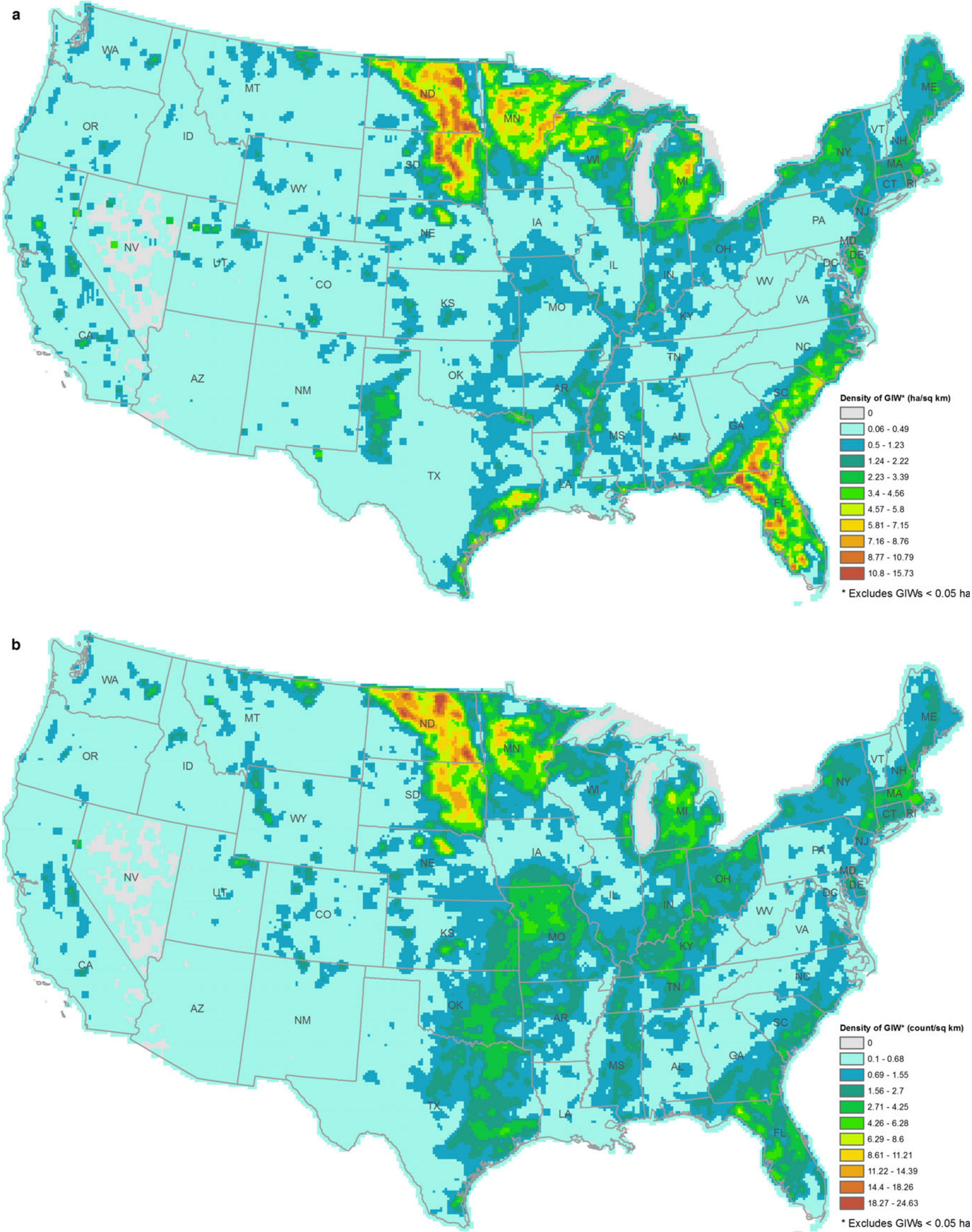

FIGURE 3. (a) Heat Map of Areal Density (ha/km^2) of Putative Geographically Isolated Wetlands (GIWs) across the Conterminous United States (U.S.). Map was generated using ArcGIS point density algorithms. (b) Heat map of count density (number of GIW polygons per km^2) of putative GIWs across the conterminous U.S. Map was generated using ArcGIS point density algorithms.

TABLE 3. Effects of Increasing Geographic Buffer Measures within Five Select Study Areas, Showing Decreased Abundance of Geographically Isolated Wetlands (GIWs) with Increasing Buffer Width (i.e., increased lotic and lentic connectivity).

Distance Buffer	Prairie Pothole Region	Delmarva Ponds	Pocosins and Carolina Bays	Texas Coastal Wetlands	California Vernal Pools
Total area of potential GIWs (ha)					
10 m	1,114,189.03	32,790.61	392,887.75	150,629.94	30,685.92
30 m	1,091,795.47	27,402.00	367,752.72	130,154.06	24,728.38
300 m	873,070.10	7,872.77	190,017.43	63,022.92	9,323.68
Percent change in abundance of GIWs compared to 10 m					
30 m	−2.0%	−16.4%	−6.4%	−13.6%	−19.4%
300 m	−21.6%	−76.0%	−51.6%	−58.2%	−69.6%

	Prairie Pothole Region	Delmarva Ponds	Pocosins and Carolina Bays	Texas Coastal Wetlands	California Vernal Pools
Proportion of total freshwater habitat as potential GIWs					
Total freshwater habitat (ha)	2,192,620.6	201,976.1	3,373,736.5	846,668.2	526,179.7
10 m	50.8%	16.2%	11.6%	17.8%	5.8%
30 m	49.8%	13.6%	10.9%	15.4%	4.7%
300 m	39.8%	3.9%	5.6%	7.4%	1.8%
Change in abundance of GIWs as a proportion of freshwater habitat (compared to 10 m)					
30 m	−1.0%	−2.7%	−0.7%	−2.4%	−1.1%
300 m	−11.0%	−12.3%	−6.0%	−10.3%	−4.1%

TABLE 4. Euclidean Distance between Putative Geographically Isolated Wetland (GIW) Edge and Nearest GIW and National Hydrography Dataset (NHD) Feature for Select Study Areas.

	Mean Distance (m)	Min Distance (m)	Max Distance (m)	Standard Deviation (m)
Prairie Pothole				
Distance to NHD feature	1,112.8	<0.1	12,089.8	1,125.1
Distance to closest GIW	80.4	<0.1	8,804.7	106.2
Delmarva Ponds				
Distance to NHD feature	241.5	0.6	1,754.4	213.4
Distance to closest GIW	159.9	0.1	3,217.8	212.3
Pocosins and Carolina Bays				
Distance to NHD feature	441.6	1.2	4,423.0	434.1
Distance to closest GIW	184.7	<0.1	14,629.1	221.8
Texas Coastal Wetlands				
Distance to NHD feature	904.9	0.3	17,815.7	1,606.5
Distance to closest GIW	184.4	<0.1	14,208.4	267.5
California Vernal Pools				
Distance to NHD feature	370.3	8.6	5,994.8	492.3
Distance to closest GIW	431.6	<0.1	8,434.9	580.2

papers (e.g., Marton *et al.*, 2015; Rains *et al.*, 2015) provide the state of the science for various functions associated with GIWs. Quantifying functions, and hence downstream effects of GIWs, is complicated by the fact that there are many vegetative (e.g., Atlantic Coastal Plain Northern Pondshore, South Florida Cypress Dome; Comer *et al.*, 2005), hydrogeomorphic (e.g., depressions, seeps, etc.; Brinson, 1993), and common descriptive (e.g., cypress domes, bogs, alvars; Tiner *et al.*, 2002) types or classes of GIWs. In addition, there are wide variations in processing rates and functions within — as well as even among — any given classification system. For instance, Lane and D'Amico (2010) quantified greater water storage potential in palustrine open water and aquatic bed GIWs *vs.* palustrine emergent marshes and palustrine scrub shrub. Lane *et al.* (2015) also found greater potential denitrification rates in emergent marsh GIWs, rates almost three times those found in forested systems (8.99 ± 5.08 μg N kg/DW/h *vs.* 3.11 ± 1.53 μg N kg/DW/h). Classifying the extent of the nation's GIW resources is the first step to better understanding the functions and subsequently sustainably managing these systems.

By our geospatial characterization of a GIW, NWI wetlands >10 m from an NHD feature, we identified almost 8.4 million putative GIWs covering almost 6.6 million ha. This estimate provides the first data-

TABLE 5. Definitions of Major NWI Water Regimes Identified with Putative Geographically Isolated Wetland (GIW) Polygons (see Cowardin *et al.*, 1979).

Water Regime	**Proportion Potential GIWs at National Scale (%)**	**Water Regime Description***
Seasonally flooded	27.5	"Surface water is present for extended periods especially early in the growing season, but is absent by the end of the growing season in most years. When surface water is absent, the water table is usually at or very near the land surface."
Temporarily flooded	22.9	"Surface water is present for brief periods during growing season, but the water table usually lies well below the soil surface for most of the season."
Permanently flooded	14.9	"Water covers the land surface throughout the year in all years."
Semipermanently flooded	14.0	"Surface water persists throughout the growing season in most years. When surface water is absent, the water table is usually at or very near the land's surface."
Intermittently exposed	8.4	"Surface water is present throughout the year except in years of extreme drought."
Saturated	6.4	"The substrate is saturated to surface for extended periods during the growing season, but surface water is seldom present."
Seasonally flooded/saturated	3.2	"Surface water is present for extended periods especially early in the growing season and when surface water is absent, substrate remains saturated near the surface for much of the growing season."

*These definitions were taken verbatim from Cowardin *et al.* (1979, p. 24), except for Seasonally Flooded/Saturated (U.S. Fish and Wildlife Service, Wetland Code Interpreter Tool, www.fws.gov/wetlands/Data/Wetland-Codes.html, accessed August, 2015).

based approximation of the extent of putative GIWs in the conterminous U.S., and falls within the bounds estimated by Likens *et al.* (2000), who postulated that no more than 20% of the wetlands of the conterminous U.S. may be geographically isolated. However, as expected there are caveats to these results further discussed below that both warrant mention and suggest areas fruitful for additional research: data age and resolution, and buffer distance selection.

Data Age and Resolution

The NWI is the finest resolution wetland data layer available at the national scale, and though higher resolution updates do intermittently occur in certain parts of the country the majority of the data are 1:58,000 or 1:80,000 scale (Tiner, 1997, 2009). This means that we cannot identify smaller objects like many depressional wetland systems (e.g., Lathrop *et al.*, 2005). In addition, the NWI is an aged data layer, with the majority of the country mapped in the 1980s, and a substantial portion of the northern Midwest and PPR still relying on wetland maps from the 1970s. The incorporation of dated wetland data layers in current GIS analyses can result in spurious identification of GIW where wetlands have already been altered or destroyed. For instance, Johnston (2013) reported annualized PPR wetland losses from the 1970s-1980s and when the study was conducted in 2011 of 5,203 ha/yr. Dahl (2014) reported annualized losses of approximately 2,510 ha/yr between 1997 and 2009 in the greater PPR. Wright and Wimberly (2013) also identified an increase in land drainage surrounding wetland systems in portions of the PPR. These changes are not, of course, restricted to the PPR. McCauley *et al.* (2013, p. 117) reported 20 years of urbanization in central Florida resulted in the destruction of 26% of "…isolated wetlands dominated by cypress (*Taxodium distichum*)…despite the fact that these wetlands are common and partially protected by legislation…" The dated NWI maps do not capture these changes; regional updates using high-resolution satellite data will substantially improve our knowledge of the existing resource.

The NHD data layer, as with the NWI layer, is very useful for a wide variety of mapping applications (e.g., Nadeau and Rains, 2007). However, many lotic systems that are less than 1.6 km in length are not mapped, and increased potential connectivity can be mapped when higher resolution data are used. For instance, Lang *et al.* (2012) found that stream lines developed using high-resolution LiDAR data instead of NHD data increased the connectivity of wetland area in a Maryland study by 15%. In addition, as with any dataset there can be substantial lag times between database revisions, and some data in the NHD dates to imagery collected in the 1950s (USGS, 2014).

Defining Connectivity

We followed established convention in using a set distance of 10 m from the edge of defined NHD

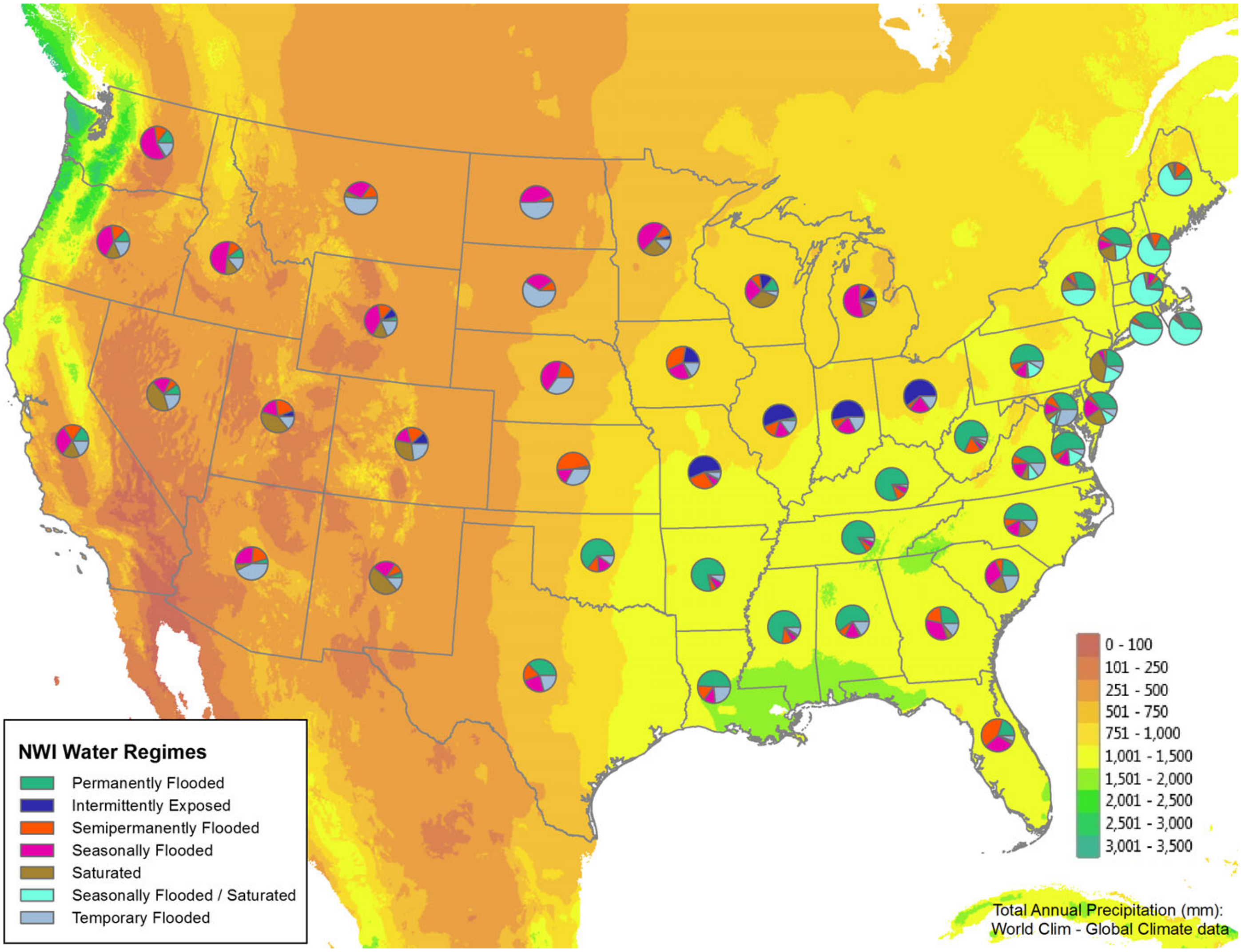

FIGURE 4. The Abundance of Putative Geographically Isolated Wetlands by the Seven Most Abundant National Wetlands Inventory Water Regimes on a State-by-State Basis, Overlaying an Abbreviated North American Map of Annual Precipitation, Suggesting Climatological Effects on Wetland Hydrologic Patterning.

features as a proxy for ecological and/or hydrological connectivity (see, e.g., Frohn *et al.*, 2009, 2011, 2012; Reif *et al.*, 2009; Lane *et al.*, 2012). Data quality expectations of the NHD follow the National Map Accuracy Standards (FGDC, 1998) such that for 1:24,000 maps, 90% of points should be mapped to within 12-14 m of corresponding ground features, depending on the map format (Lang *et al.*, 2012). We incorporated NHD flow-lines and polygons that statically defined dynamic aquatic systems across the nation, including data that were in some cases greater than 60 years old. While we did not contrast 10-m to either 12- or 14-m buffers, to assess how a connectivity distance greater than our 10-m measure would affect our results, we did increase the buffers from 10 to 30 m and then again to 300 m in five areas selected for buffer analysis (see Figure 1). Limited changes in the abundance of GIWs as a proportion of freshwater habitat occurred when we increased the buffers from 10 to 30 m. This suggests that, as Tiner (2003b) and Lane *et al.* (2012) found, the differences between 10 m and either 12 or 14 m, and indeed between 10 and 30 m at the national scale could be *relatively* inconsequential, though it may have greater impact at the regional scale. However, increasing the buffer defining connectivity to 300 m substantially decreased the abundance of potential GIWs (i.e., increased the number of connected systems), especially in areas of the country with substantial stream network densities.

Local and site-specific analyses of connectivity can be both critical and contentious (Downing *et al.*, 2003; Reitze and Harrison, 2007; Adler, 2015). The use of geospatial distance simplifies the process for national-scale analyses, but does not obviate the need for subsequent advanced analyses to improve the approach. For instance, wetland connectivity may be defined as located within a floodplain or riparian area rather than through the use of distance measures (Wharton *et al.*, 1982; Fennessy and Cronk, 1997). This would require efforts to better identify and define the existing floodplains of a given system (e.g., Sangwan and Merwade, 2015), and remains a worthy and timely research area.

Ultimately, we agree with Tiner (2003a), Rains *et al.* (2006), Mushet *et al.* (2015), Leibowitz (2015), and others (e.g., Subalusky *et al.*, 2009; Wilcox *et al.*, 2011; Lang *et al.*, 2012; McLaughlin *et al.*, 2014; Golden *et al.*, 2015) who argue that wetlands identified as geographically isolated can be frequently connected to other systems by multiple pathways. Furthermore, these connections exist along a continuum from frequently connected to infrequently connected (Ward, 1989; see also USEPA, 2015). Fully assessing where certain wetland typologies exist along that continuum remains an area of active research. Incorporating floodplain hydrogeomorphology and the frequency, duration, and intensity of connectivity within the active floodplain and defining areas outside the floodplain are particularly germane to improving our current understanding of connectivity and geographic isolation (Leibowitz *et al.*, 2008; Thorp *et al.*, 2010; USEPA, 2015).

Examples of Data Application

We anticipate that these data will be useful for studies across multiple disciplines, including habitat, biogeochemical, and hydrological studies and the data are available by contacting the first author. For instance, depressional wetlands are areas of amphibian richness and abundance (e.g., Gibbons *et al.*, 2006; Calhoun and deMaynadier, 2008). Wetland complexes composed of depressions of differing sizes, depths, and structures would provide the greatest abundance of habitat and the highest population resilience (Ritchie, 1997; Uden *et al.*, 2014). Knowing the density of GIWs, as well as the distance between wetland features could improve management decisions, especially for amphibians (Smith and Green, 2005). For instance, Mushet *et al.* (2013) found homogenous genetic structure in sampled northern leopard frogs (*Lithobates pipiens*) across a 68-km study area in the PPR, suggesting the amphibians readily moved between wetlands, and between wetlands and streams. This is supported by the proximity of putative GIWs in the PPR (80.4 ± 106.2 m), providing ample breeding sites and refugia during droughts. We draw no additional specific conclusions from our basic analyses other than to note distance measures may be informative to land-management decisions based on protecting habitat for dispersing organisms, but there are many opportunities to utilize the data for additional intensive analyses and refinement (e.g., Downing, 2010; Larsen *et al.*, 2012; Cohen *et al.*, 2016).

Several studies have modeled the influence of depressional wetlands on stream flow (e.g., Shook and Pomeroy, 2011; Shook *et al.*, 2013; Pomeroy *et al.*, 2014; Evenson *et al.*, 2015; Golden *et al.*, 2015). Providing a base-layer of putative GIWs could improve the parameterization of models to more accurately account for GIW effects potentially decoupling storm flows and/or maintaining baseflows (Golden *et al.*, 2014; Evenson *et al.*, 2015). Similarly, recent biogeochemical analyses have targeted nutrient assimilation and transformational functions within GIWs (Dierberg and Brezonik, 1984; Euliss *et al.*, 2006; Rains *et al.*, 2008; Gleason *et al.*, 2009; Lane *et al.*, 2015; Lane and Autrey, 2015; Marton *et al.*, 2015). Expanding the spatial extent of these studies and focusing on certain vegetation or hydrogeomorphological classes could improve our knowledge of the influence of GIWs on local and landscape nutrient dynamics.

Lastly, GIWs exist at the interface between aquatic and terrestrial systems and are typically (though not exclusively) dependent on precipitation runoff and near-surface groundwater flows to maintain functioning wetland hydrology (Winter and LaBaugh, 2003; USEPA, 2015). Many beneficial wetland functions result from saturated or ponded soil conditions (e.g., nutrient biogeochemical cycling [Morse *et al.*, 2012; Marton *et al.*, 2015], amphibian [Semlitsch *et al.*, 2013] and avian habitat [Mitchell *et al.*, 1992]), and these functions are affected by the seasonality of the hydropatterns and hydroperiods of these systems. Our putative GIW geodatabase includes NWI water regime information for each identified system (see Table 5) with water regime closely matching precipitation patterns (see Figure 4). We anticipate that this data could be useful for large-scale (e.g., watershed hydrologic and atmospheric) models that incorporate small-scale yet abundant GIW landscape elements (Forman, 1995). For instance, seasonally and temporarily flooded GIWs would be expected to have higher organic matter oxidation rates resulting in greater atmospheric release of CO_2 and CH_4 affecting the atmospheric concentration of greenhouse gasses (e.g., Gleason *et al.*, 2009). Similarly, denitrification rates would be higher in wetlands with longer water regimes and saturated or ponded soils (all other things being equal). Global climate change and accompanying changes in precipitation patterns and temperature may affect transformation rates of nutrients and metals (e.g., mercury methylation; Ullrich *et al.*, 2001) as well as affect the frequency and depth of ponding and soil saturation for other wetland functions (Junk *et al.*, 2013). The data may also inform amphibian models as permanently flooded wetlands may provide refugia for over-wintering organisms (Mushet *et al.*, 2013). Conversely, the permanently flooded systems may be more likely to host fish that prey on amphibians, creating a potential population sink. Network models or agent-based approaches that incorporate water regime details and geospatial data may realize improved performance.

SUMMARY

We identified a remarkable abundance of putative GIWs by applying a distance-based definition of connectivity to existing national datasets. Approximately 16% of the nation's conterminous freshwater resources may be GIWs. These systems occurred throughout the nation, with high densities in certain ecoregions. Changing the working definition of connectivity to include a wider swath buffering stream, river, and lake (etc.) features — not surprisingly — resulted in GIW extent decreases. These results provide the first national data-based estimate on the abundance of putative GIWs. Though conducted using a geospatially based metric as a proxy for hydrologically or ecologically connected wetlands, this study provides timely data useful to informing policy decisions on the wise management of wetland resources (Adler, 2015; Alexander, 2015). More highly refined studies using remotely sensed data with improved resolution or incorporating additional GIS datasets (e.g., soils, DEMs, etc.) will improve upon this product, as will including the use of floodplain and other hydrogeomorphic features. The potential utility of this GIW dataset, we hope, goes beyond quantification of an under-reported resource.

APPENDIX 1: NHD FEATURE TYPE EXPLANATION

We developed a process to characterize which NHD features to buffer. We buffered NHD flowline and area features given in Table A1. However, we followed the flowchart (Figure A1) to further scrutinize and identify NHD waterbodies to ensure that

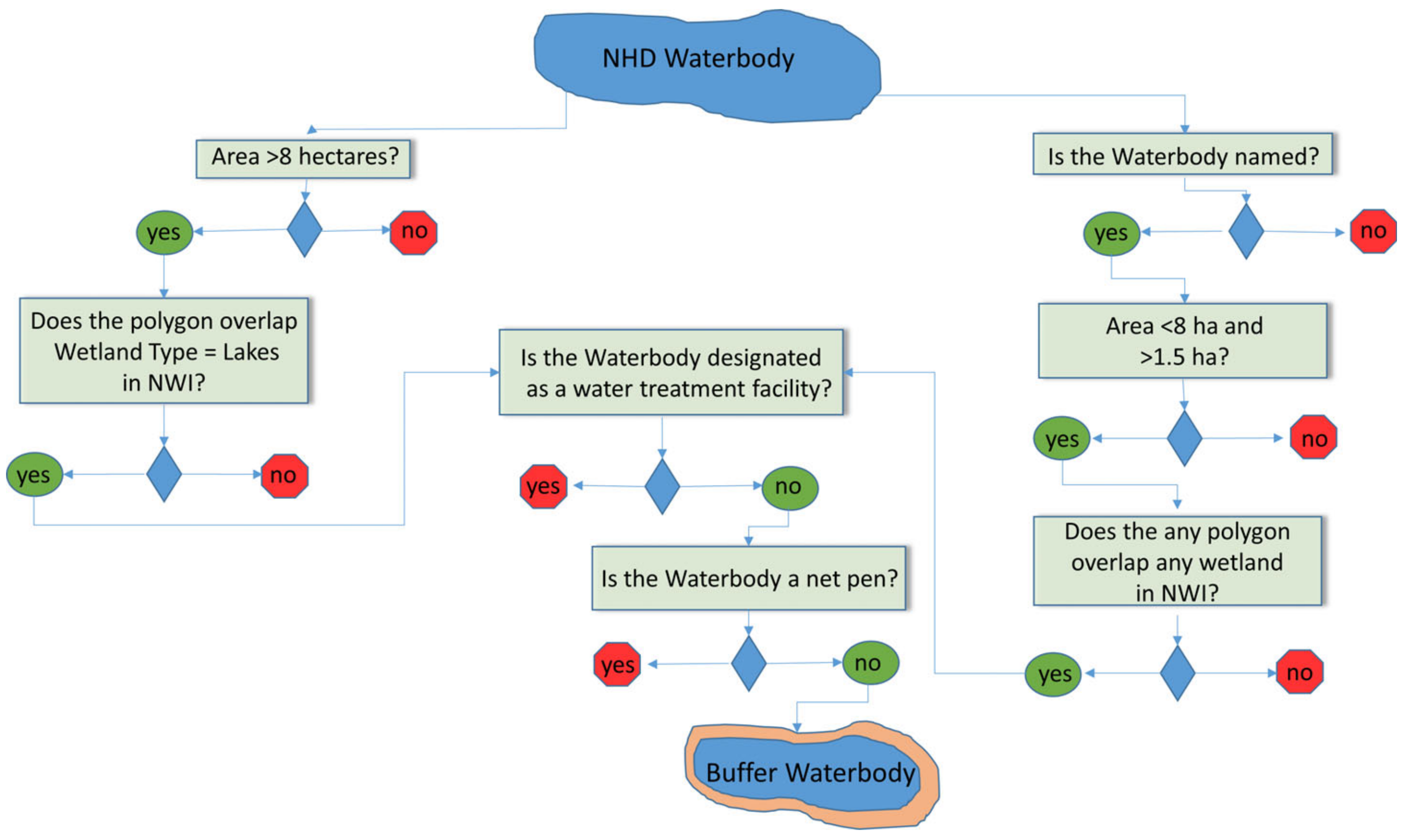

FIGURE A1. Decision-Tree Diagram to Determine Which National Hydrography Dataset Waterbodies to Apply Our 10-, 30-, or 300-m Geospatial Buffer.

TABLE A1. National Hydrography Dataset (NHD) Features to Which a Geospatial Buffer of 10 m (as well as 30 m and 300 m in select areas) Were Applied.

NHD Data Layer	Feature Type Code	Description of Feature Type
Flowline	460	Streams/rivers
	336	Canal/ditches
	558 (where GNIS name is not null)	Artificial paths
	566	Coastlines
Area	460	Streams/rivers
Waterbody	390	Lakes/ponds
	436	Reservoirs

we did not mistakenly buffer a system that could be a potential GIW.

APPENDIX 2: AGGREGATING WITH POLYGON NEIGHBORS TOOL DESCRIPTION

The majority of the NWI was aggregated using a combination of an ArcGIS tool called Polygon Neighbors and an in-house Python script (Python Software Foundation, Wilmington, Delaware, version 2.7). The Polygon Neighbors tool builds a table that identifies which polygons are adjoining (Figure A2). The

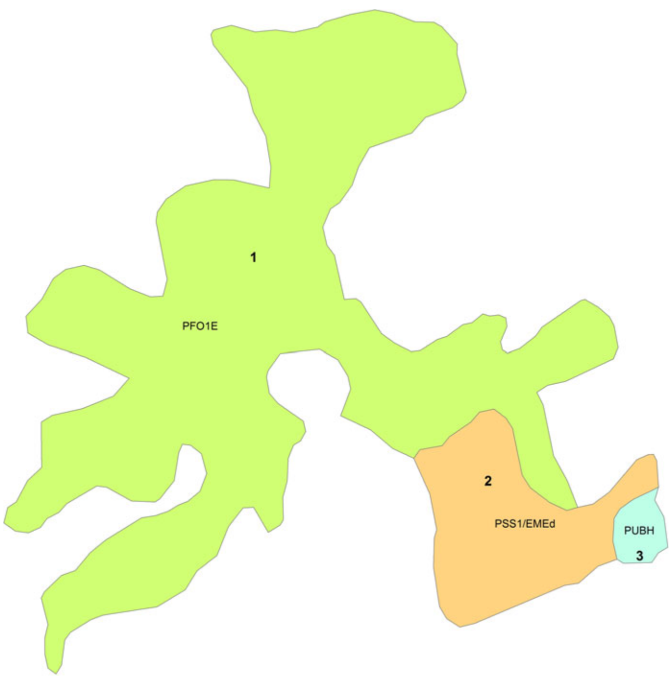

FIGURE A2. Example of Polygon Neighbors Tool Identifying Adjoining Polygons. In this example, the tool has identified that Polygon 2 is a neighbor of both Polygons 1 and 3, but it has not found a relationship between Polygons 1 and 3.

TABLE A2. Example of Final Process Identifying Adjoining Polygons and Assigning Unique Final_ID to Adjoining Systems.

Polygon ID	Neighbor ID	Final_ID
1	2	ID_1
2	1	ID_1
2	3	ID_1
3	2	ID_1

Python script uses the results table from the Polygon Neighbors analysis to establish a relationship between all adjoining polygons and adds a unique ID called Final_ID. After the Python script is completed, polygons are dissolved into a single polygon based on Final_ID (Table A2).

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